

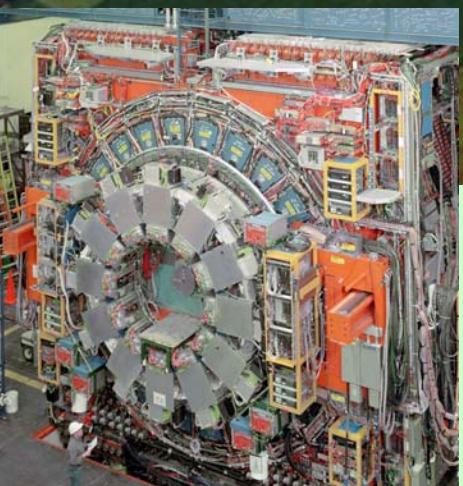
Diboson Physics at the Tevatron



2006/03/20



2004/05/09

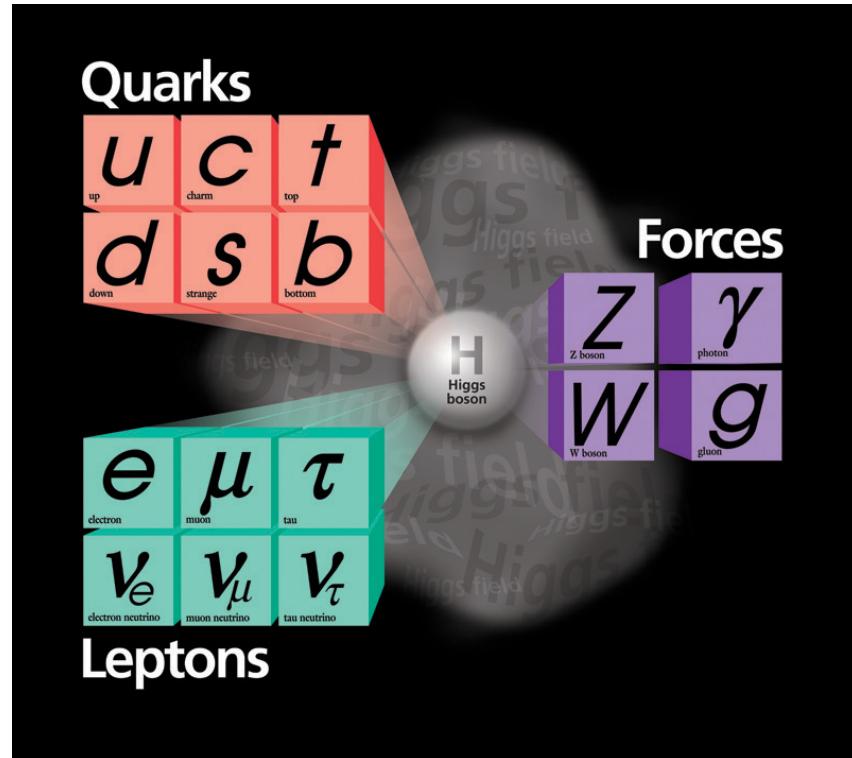


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...on behalf of the CDF & DØ Collaborations



Outline

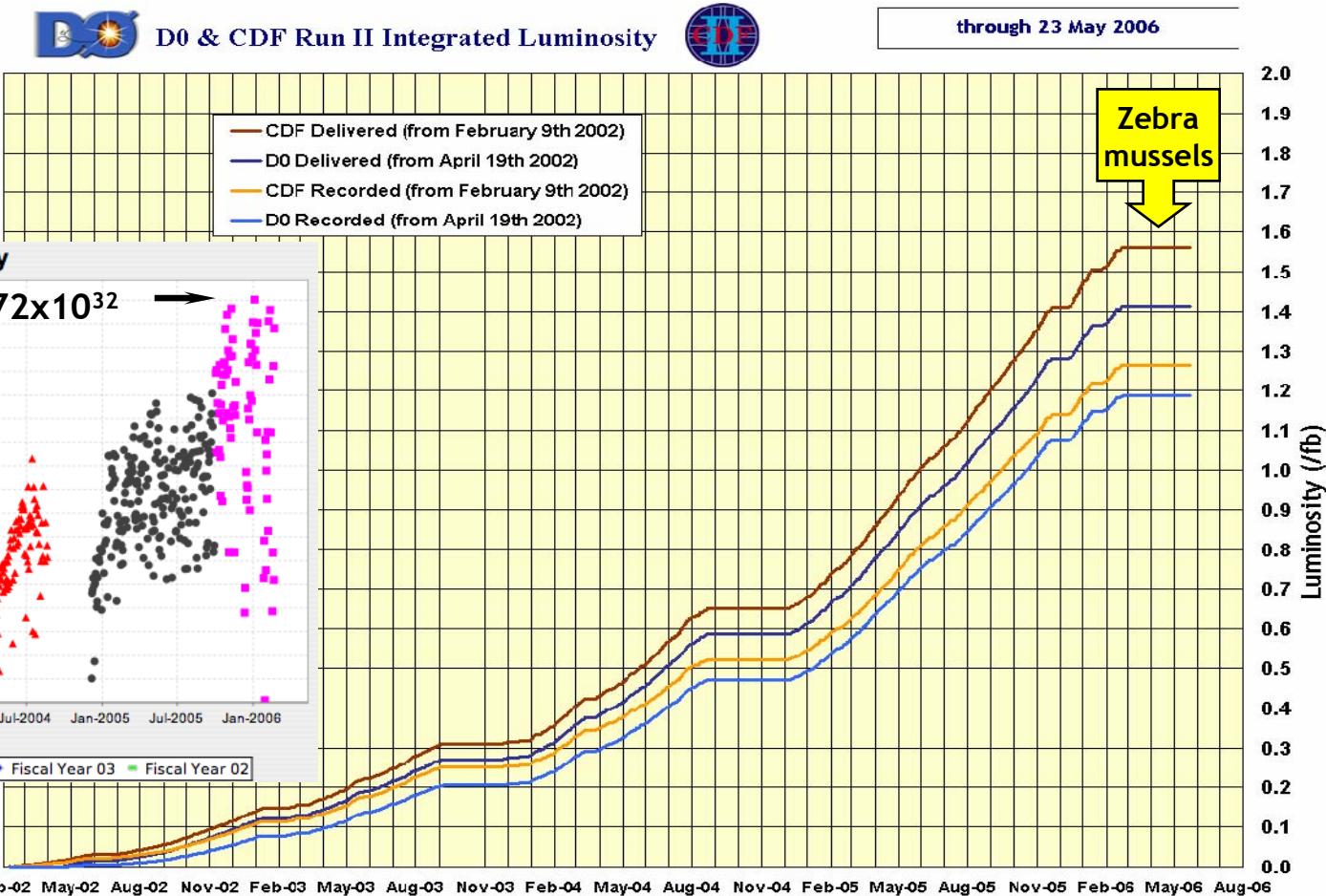
- Tevatron Performance
- DØ Detector
- Diboson Production at the Tevatron
- Cross Sections and Anomalous Couplings
 - WW
 - WZ
 - W γ
 - Z γ
- Summary



See other related talks at this conference:

- Tevatron W & Z Production & Asymmetries: Dave Waters (Univ College London)
- Higgs Searches at the Tevatron: Lars Sonnenschein (LPNHE Paris)

Tevatron Performance



- Tevatron Collider with both D0 and CDF operating successfully
- Tevatron delivered $\int L dt > 1.4 fb^{-1}$
 - recorded $> 1 fb^{-1}$ per experiment
 - peak luminosities $\sim 1.7 \times 10^{32} cm^{-2} s^{-1}$
 - weekly integrated luminosity $\sim 20 pb^{-1}/week$
- Datasets used for results reported here range from ~ 0.2 to $0.8 fb^{-1}$

- Silicon detector and scintillating fiber tracker in 2.0 T solenoidal field

- Coverage up to $|\eta| = 2.5$

- Liquid Argon/Uranium calorimeters

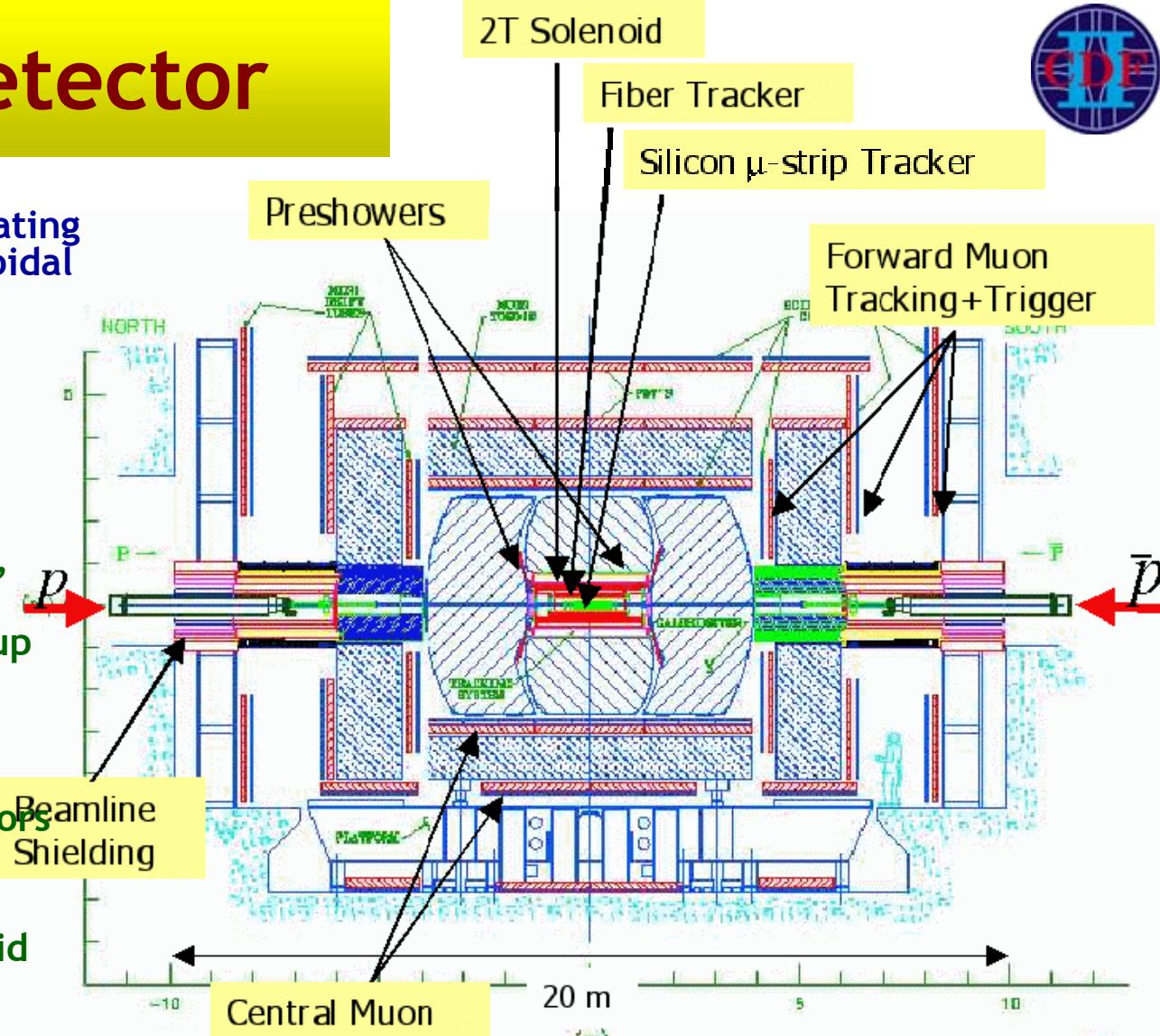
- Central and two forward calorimeters
- Stable, uniform response, radiation hard
- Hermetic with coverage up to $|\eta| = 4.2$

- Muon System

- Coverage up to $|\eta| = 2.0$
- Three layers of scintillators and drift tubes
- Central and Forward
- A layer - inside 1.8T toroid magnet
- Shielding reduces backgrounds by 50-100x

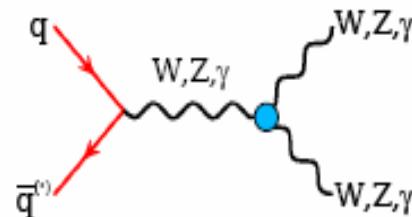
- Three Level Trigger

- L1/L2/L3 ~ 1800/1000/50 Hz



Electroweak analyses make use of the full detector capabilities

- Measure cross sections and anomalous couplings
 - Probe non-Abelian nature of $SU(2)_L \otimes U(1)_Y \rightarrow$ gauge boson self-interactions
 - Observation of events above Standard Model expectation would indicate new physics
- Excursions from the SM can be described via effective Lagrangian:



$q\bar{q}' \rightarrow W^{(*)} \rightarrow W\gamma : WW\gamma$ only
$q\bar{q}' \rightarrow W^{(*)} \rightarrow WZ : WWZ$ only
$q\bar{q} \rightarrow Z/\gamma^{(*)} \rightarrow WW : WW\gamma, WWZ$
$q\bar{q} \rightarrow Z/\gamma^{(*)} \rightarrow Z\gamma : ZZ\gamma, Z\gamma\gamma$
$q\bar{q} \rightarrow Z/\gamma^{(*)} \rightarrow ZZ : ZZ\gamma, ZZZ$
Absent in SM

$$L_{WWV} / g_{WWV} = \boxed{g_V^1} (W_{\mu\nu}^+ W^{\mu\nu} V^\nu - W_\mu^+ V_\nu W^{\mu\nu}) + \boxed{\kappa_V} W_\mu^+ W_\nu V^{\mu\nu} + \frac{\boxed{\lambda_V}}{M_W^2} W_{\lambda\mu}^+ W_\nu^\mu V^{\nu\lambda}$$

where $V = Z, \gamma$

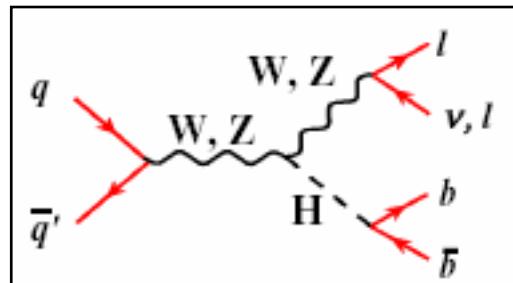
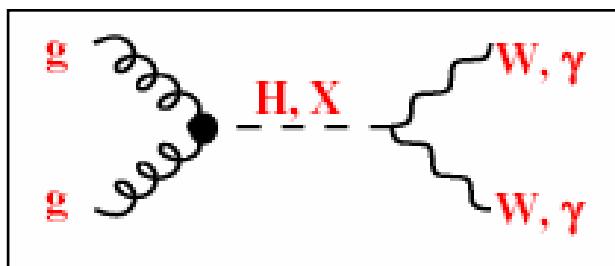
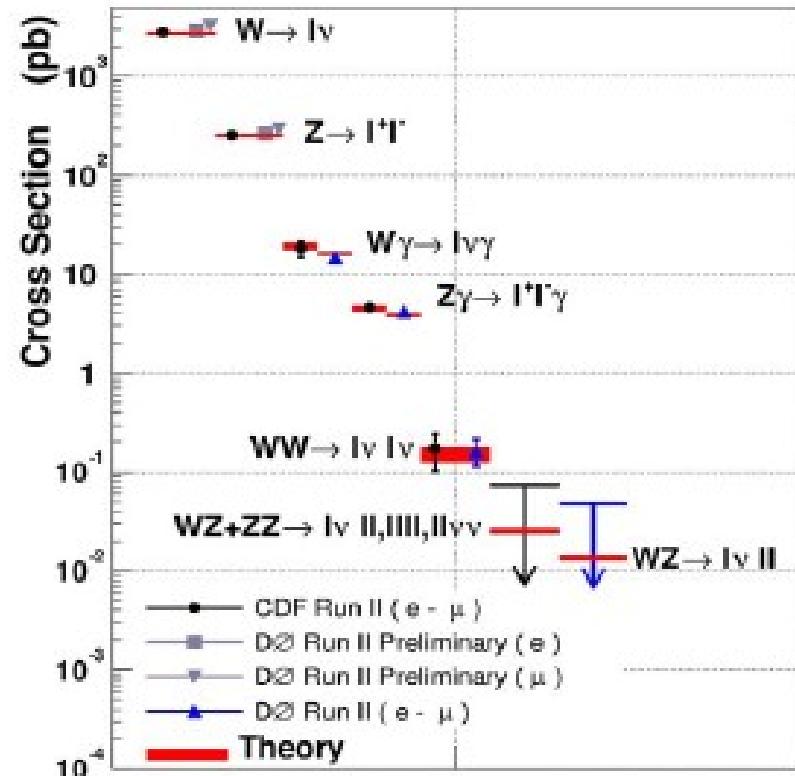
In SM:

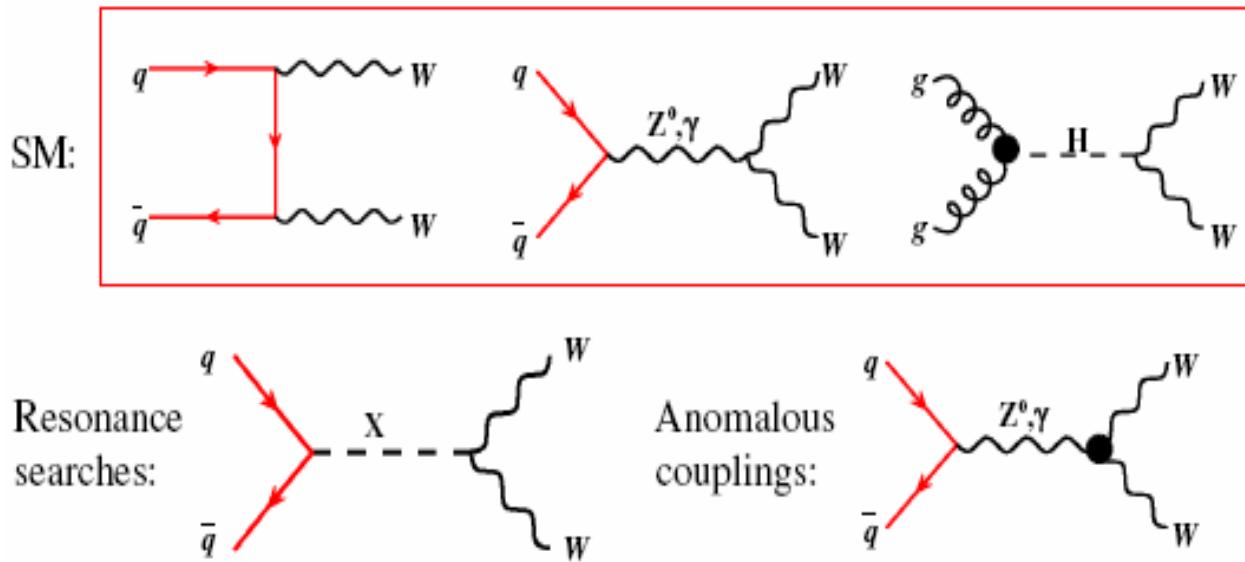
$$g_V^1 = \kappa_V = 1, \quad \lambda_V = 0$$

Determine deviation from SM values:

$$\Delta g_V^1 = g_V^1 - 1, \quad \lambda_V, \quad \Delta \kappa_V = \kappa_V - 1$$

- Diboson production cross section is small
 - $10^{-2} - 10^{-4}$ of single boson production cross section
- Look for final states with W/Z decaying to e or μ
 - Smaller branching ratio but cleaner signal
- Diboson production is an important background to other high p_T processes
 - Top pair, Higgs, SUSY



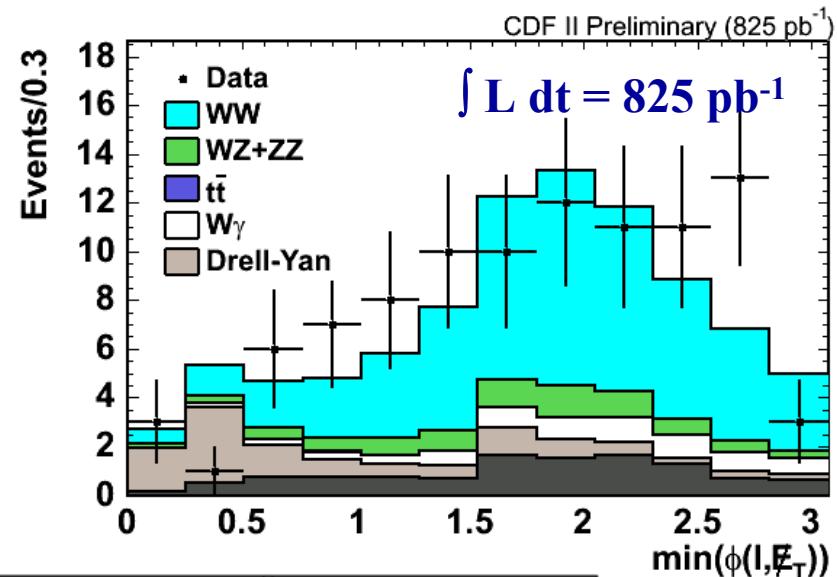


- Sensitive to WWZ / $WW\gamma$ couplings
- Dilepton channel provides cleanest signature: ee , $\mu\mu$ or $e\mu$ accompanied by missing E_T
- Main background processes: $W+j/\gamma$, dijet, Drell-Yan, top pairs, WZ , ZZ
- Theory prediction for production cross section is **12.0-13.5 pb** (*J. Ohnemus, PRD 441403 (1991); PRD 50, 1931 (1994); J.M. Campbell and R.K. Ellis, PRD 60, 113006 (1999)*) — accessible at Tevatron Run II already with a couple of 100 pb^{-1} .

Event Selection

- 2 opposite-signed leptons (e, μ) w/ $p_T > 20$ GeV
- Missing transverse energy (MET) > 25 GeV
- If both leptons are same flavor and $76 < M_{ll} < 106$, then require $\text{MET}/\sqrt{(\sum E_T)} > 3.0$
- $\Delta\phi$ (MET, nearest l) > 0.3 if MET < 50 GeV
- 0 jets ($E_T > 15$ GeV and $|\eta| < 2.5$)

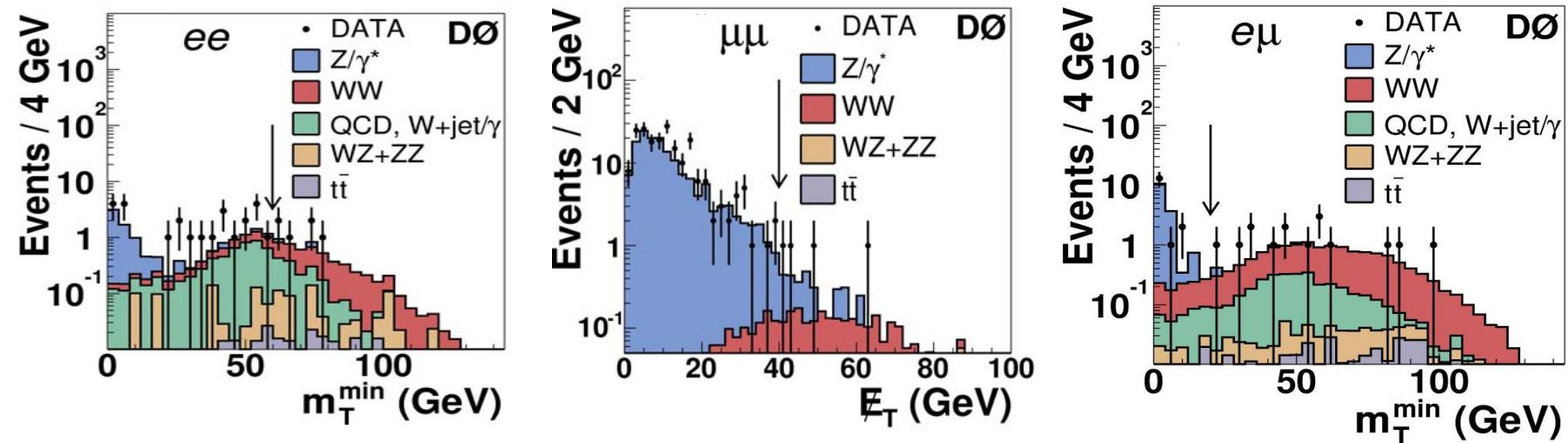
● Observe 95 events with an expected signal and background of 52.4 ± 4.3 and 37.8 ± 4.8 respectively



Mode	ee	$e\mu$	$\mu\mu$	ll
WW	$12.8 \pm 0.1 \pm 1.1$	$28.8 \pm 0.1 \pm 2.4$	$10.7 \pm 0.1 \pm 0.9$	$52.4 \pm 0.1 \pm 4.3$
Drell-Yan	$5.0 \pm 0.5 \pm 1.3$	$3.8 \pm 0.4 \pm 1.0$	$3.0 \pm 0.4 \pm 0.8$	$11.8 \pm 0.8 \pm 3.1$
$t\bar{t}$	$0.1 \pm 0.0 \pm 0.0$	$0.1 \pm 0.0 \pm 0.0$	$0.0 \pm 0.0 \pm 0.0$	$0.2 \pm 0.0 \pm 0.0$
WZ+ZZ	$3.6 \pm 0.0 \pm 0.4$	$0.9 \pm 0.0 \pm 0.1$	$3.4 \pm 0.0 \pm 0.3$	$7.9 \pm 0.0 \pm 0.8$
$W\gamma$	$3.6 \pm 0.1 \pm 0.7$	$3.2 \pm 0.1 \pm 0.7$	$0.0 \pm 0.0 \pm 0.0$	$6.8 \pm 0.2 \pm 1.4$
W+jets	$3.0 \pm 0.2 \pm 0.7$	$6.7 \pm 0.4 \pm 2.0$	$1.3 \pm 0.2 \pm 0.5$	$11.0 \pm 0.5 \pm 3.2$
Sum Bkg	$15.2 \pm 0.6 \pm 1.7$	$14.8 \pm 0.6 \pm 2.3$	$7.8 \pm 0.4 \pm 1.0$	$37.8 \pm 0.9 \pm 4.7$
Expected	$28.0 \pm 0.6 \pm 2.0$	$43.7 \pm 0.6 \pm 3.3$	$18.5 \pm 0.4 \pm 1.3$	$90.2 \pm 0.9 \pm 6.4$
Data	29	47	19	95

$$\sigma = 13.6 \pm 2.3 (\text{stat}) \pm 1.6 (\text{sys}) \pm 1.2 (\text{lum}) \text{ pb}$$

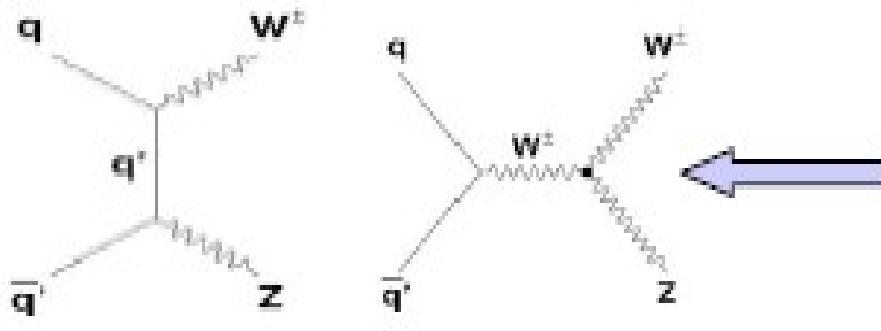
- Look for two oppositely charged leptons (e, μ) plus missing ET
- DØ and CDF selection for WW signal are similar
- Found 25 (6 ee, 4 $\mu\mu$, 15 $e\mu$) candidates in $\sim 237\text{pb}^{-1}$
- Expected background $8.1 \pm 0.6 \text{ (stat)} \pm 0.6 \text{ (sys)} \pm 0.5 \text{ (lumi)}$
- First 5.2σ observation of WW production at the Tevatron



$$\sigma(\text{WW}) = 13.8^{+4.3}_{-3.8} \text{ (stat)}^{+1.2}_{-0.9} \text{ (sys)} \pm 0.9 \text{ (lumi)} \text{ pb}$$

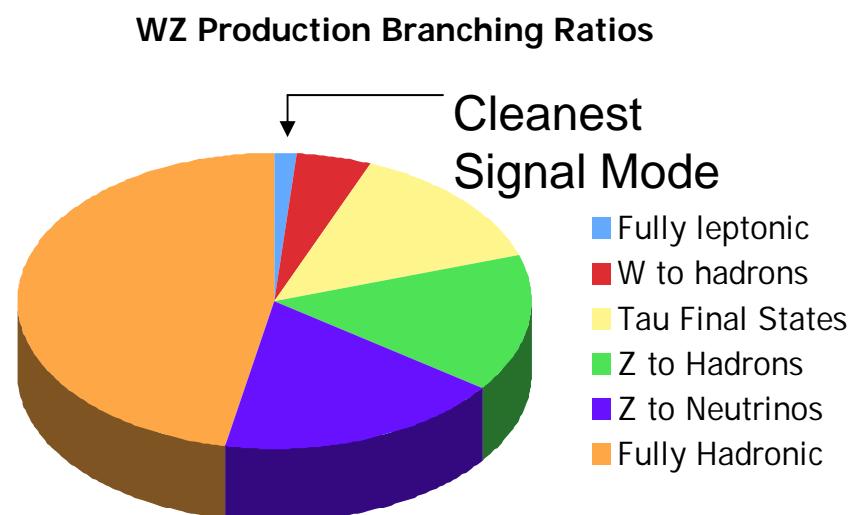
PRL 94, 151801 (2005)

- Both CDF and DØ measurements of WW cross section are consistent with the SM expectation



- Sensitive to purely WWZ vertex
(WW is sensitive to WWZ /WW γ)
- WZ production unavailable at e⁺e⁻ colliders

- Search for WZ production in 3 leptons (eee, ee μ , e $\mu\mu$, $\mu\mu\mu$) + missing E_T
- Distinct, but rare signature:
 - $\sigma(pp\bar{p} \rightarrow WZ) = 3.7 \pm 0.1 \text{ pb}$
(J.M. Campbell and R.K. Ellis, PRD 60, 113006 (1999))
 - Branching fraction ~1.5%
- Background processes: Z+jet(s), ZZ, Z γ , ttbar production



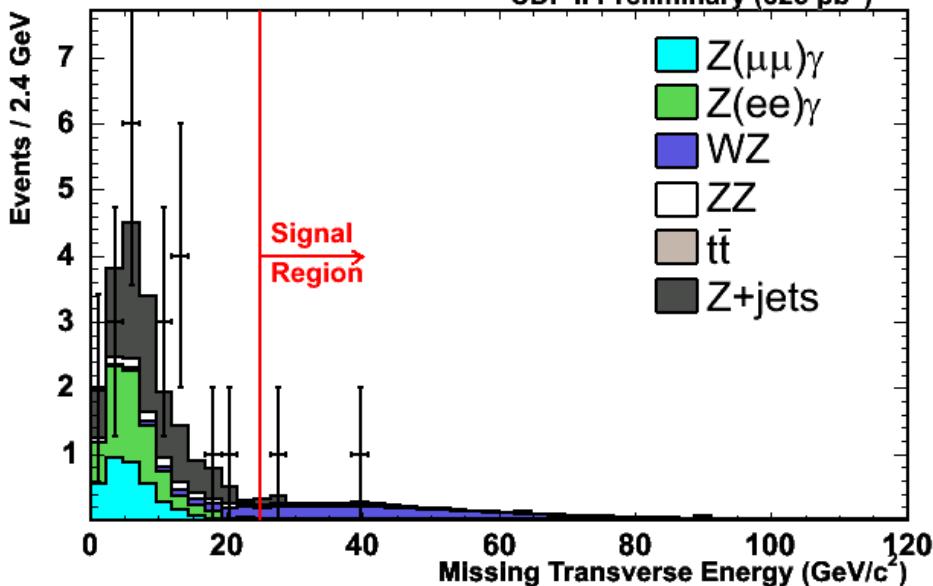
- $\int L dt = 825 \text{ pb}^{-1}$

- Event Selection

- 3 leptons (e, μ) w/ $p_T > 20, 10, 10 \text{ GeV}$
- $76 < M_{ll} < 116 \text{ GeV}$
- MET $> 25 \text{ GeV}$

- Observe 2 events with an expected signal and background of 3.7 ± 0.3 and 0.9 ± 0.2 respectively

$\sigma(WZ) < 6.34 \text{ pb (95\% C.L.)}$



Signal:

WZ: $3.72 \pm 0.02 \text{ (stat.)} \pm 0.15 \text{ (syst.)}$

Backgrounds:

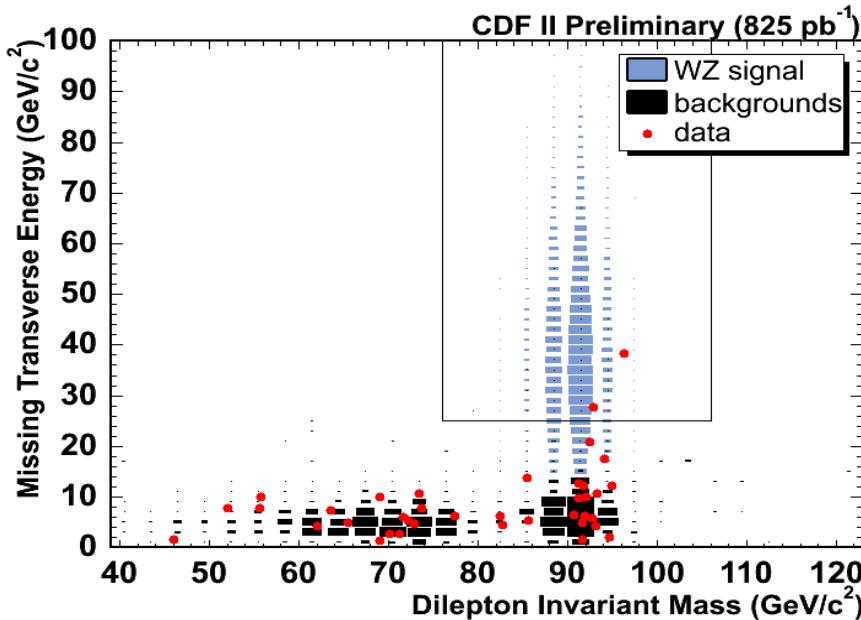
ZZ: $0.50 \pm 0.01 \text{ (stat.)} \pm 0.05 \text{ (syst.)}$

$Z\gamma$: $0.03 \pm 0.01 \text{ (stat.)} \pm 0.01 \text{ (syst.)}$

$t\bar{t}$: $0.05 \pm 0.01 \text{ (stat.)} \pm 0.01 \text{ (syst.)}$

$Z+\text{jets}$: $0.34 \pm 0.07 \text{ (stat.)} \quad {}^{+0.15}_{-0.09} \text{ (syst.)}$

Total: $0.92 \pm 0.07 \text{ (stat.)} \quad {}^{+0.16}_{-0.10} \text{ (syst.)}$



- $\int L dt = 300 \text{ pb}^{-1}$
- Observed 3 events (1eee, 2 $\mu\mu$) with an expected signal and background of 2.0 ± 0.2 and 0.7 ± 0.1 respectively
- Prob (3 events | 0.7 bkg) = 3.5%

$\sigma < 13.3 \text{ pb at 95 \% C.L.}$

$\sigma = 4.5^{+3.8}_{-2.6}(\text{stat+sys}) \text{ pb}$

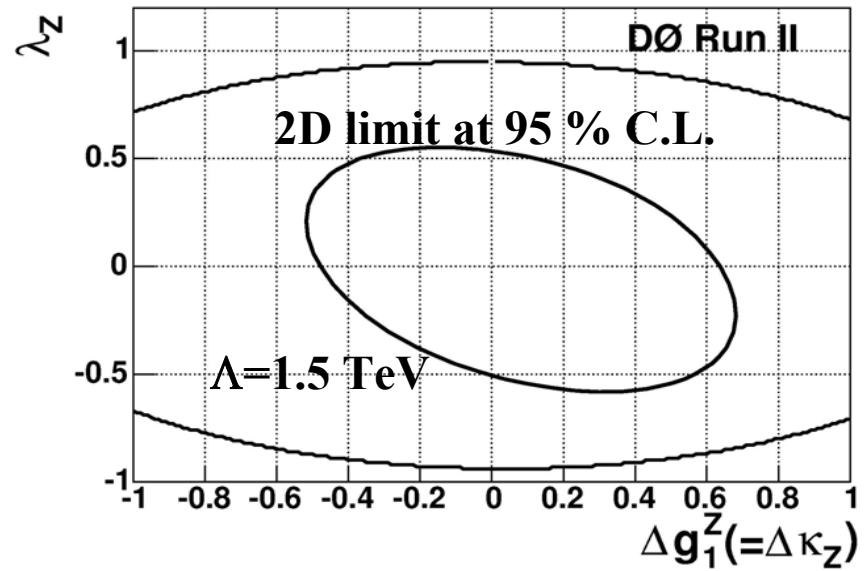
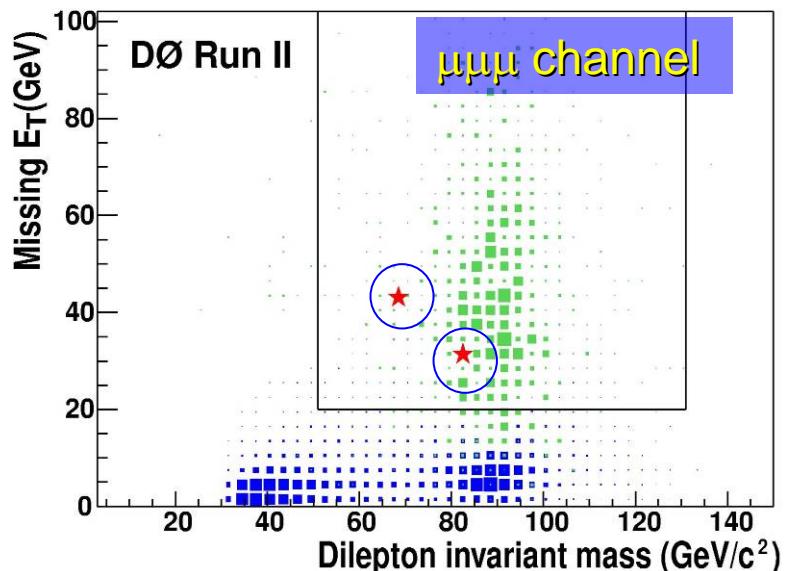
- Anomalous Couplings limits:

1 D limits at 95% C.L. for $\Lambda=1 \text{ TeV}$:

$$\begin{aligned} -0.53 &< \lambda_Z < 0.56 \\ -0.57 &< \Delta g^Z < 0.76 \\ -2.0 &< \Delta \kappa_Z < 2.4 \end{aligned}$$

PRL 95, 141802 (2005)

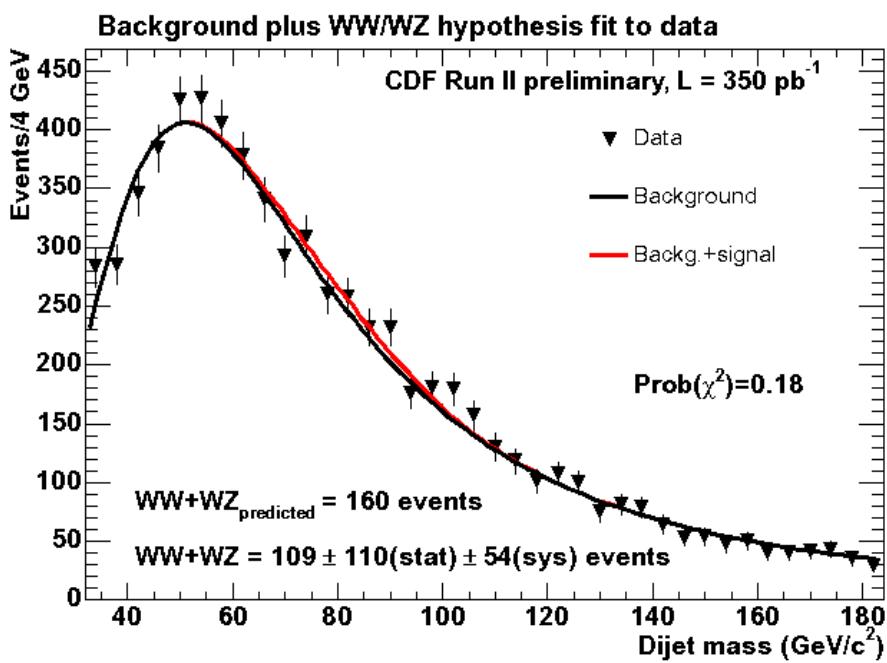
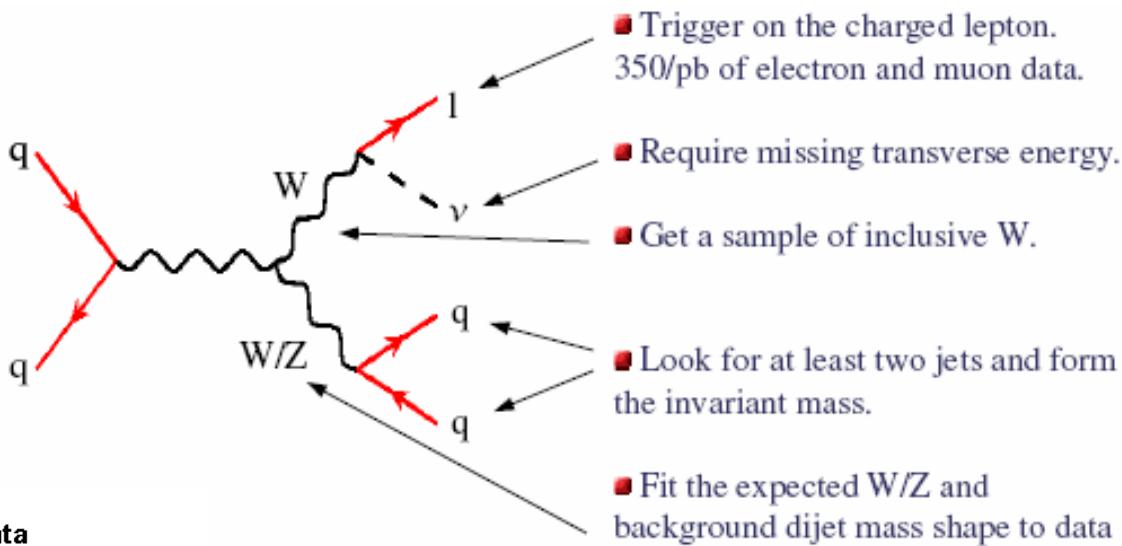
- Best limits if Δg^Z , $\Delta \kappa_Z$ and λ_Z from direct, model-independent measurement



- Higher branching fraction, but large W+jets background

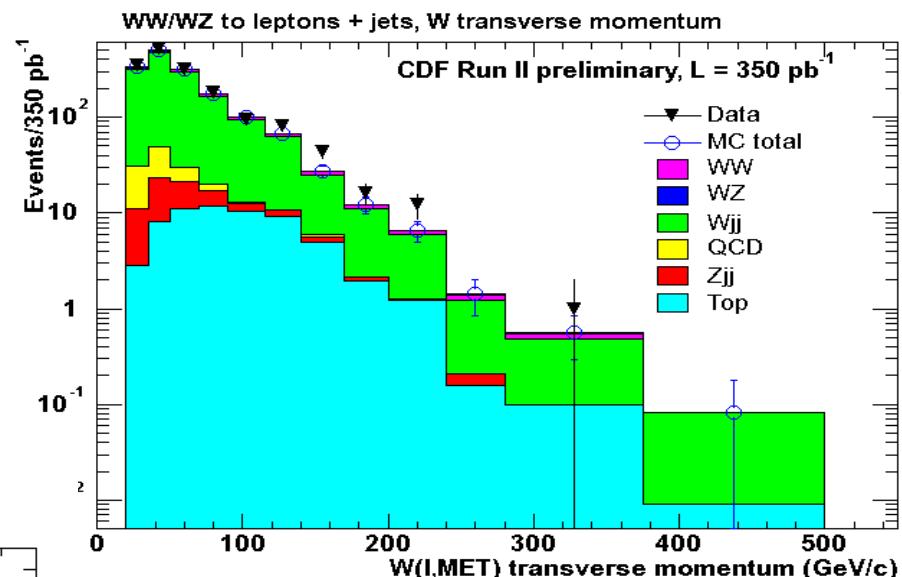
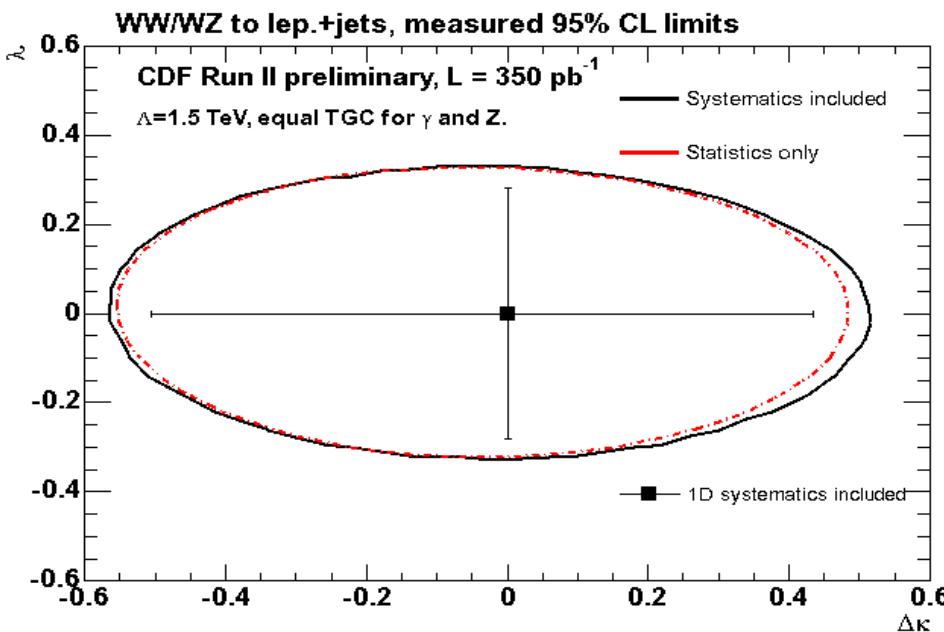
Event Selection

- Isolated Lepton $p_T > 25$ GeV
- ≥ 2 jets w/ $E_T > 15$ GeV
- MET > 25 GeV
- Dijet mass 32-184 GeV



$\sigma(\text{WW}+\text{WZ}) < 36 \text{ pb at 95\% C.L.}$

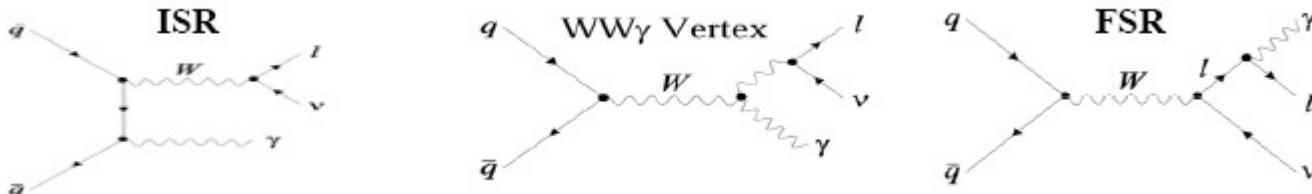
- W transverse momentum most sensitive for AC limits
 - formed from the lepton p_T and the MET (neutrino)
- Full spectrum fitted for the AC hypothesis and used for setting the limits



- Measured anomalous couplings limits, 1D, 95% C.L.
 - Assume equal TGC for Z and γ , $\Lambda = 1.5 \text{ TeV}$:

$$\begin{aligned}-0.51 < \Delta \kappa < 0.44 \\ -0.28 < \lambda < 0.28\end{aligned}$$

- Three diagrams at tree level



- Sensitive to $WW\gamma$ coupling
- Study final states with W decaying to electron or muon - events with $e/\mu + \gamma + \text{missing } E_T$.
- Main background from $W+\text{jets}$ and $Z+X$ (lepton from Z lost/mis-identified).
- Efficient photon identification crucial
 - $E_T > 7 \text{ GeV (CDF), } E_T > 8 \text{ (D0) GeV,}$
 - $|\eta| < 1.0 \text{ (CDF), } |\eta| < 1.1 \text{ (D0) GeV}$
- Highest sensitivity to Anomalous Coupling at high photon E_T and $M_T(W, \gamma)$
- FSR photon in $W\gamma$ is sort of “background” for studying AC – apply $\Delta R(\text{lepton}, \gamma) > 0.7$ to suppress FSR contribution
- Theoretical cross section $\sim 16-19 \text{ pb}$ (*U.Baur, E.L. Berger, PRD 41, 1476 (1990)*)



W γ Production



Channel	DØ		CDF	
	e $\nu\gamma$	$\mu\nu\gamma$	e $\nu\gamma$	$\mu\nu\gamma$
$\int L dt, pb^{-1}$	162	134	202	192
W γ	51.2 ± 11.5	89.7 ± 13.7	126.8 ± 5.8	95.2 ± 4.9
Total Bkgrd	60.8 ± 4.5	71.3 ± 5.2	67.3 ± 18.1	47.3 ± 7.6
# Observed	112	161	195	128
A* ϵ	2.3%	4.4%	3.3%	2.4%
$\sigma^* BR, pb$	$13.9 \pm 2.9 \pm 1.6$	$15.2 \pm 2.0 \pm 1.1$	$19.4 \pm 2.1 \pm 2.9$	$16.3 \pm 2.3 \pm 1.8$

● Cross section from combined electron and muon channels

DØ: $\sigma(W\gamma, E_T^\gamma > 8 \text{ GeV}, \Delta R(\ell, \gamma) > 0.7) = 14.8 \pm 1.6(stat) \pm 1.0(sys) \pm 1.0(lum) \text{ pb}$

SM expectation : $16.0 \pm 0.4 \text{ pb}$

PRD 71, 091108 (2005)

CDF: $\sigma(W\gamma, E_T^\gamma > 7 \text{ GeV}, \Delta R(\ell, \gamma) > 0.7) = 18.1 \pm 3.1(tot.) \text{ pb}$

SM expectation: $19.3 \pm 1.4 \text{ pb}$

PRL 94, 041803 (2005)

- Photon E_T sensitive to presence of anomalous coupling

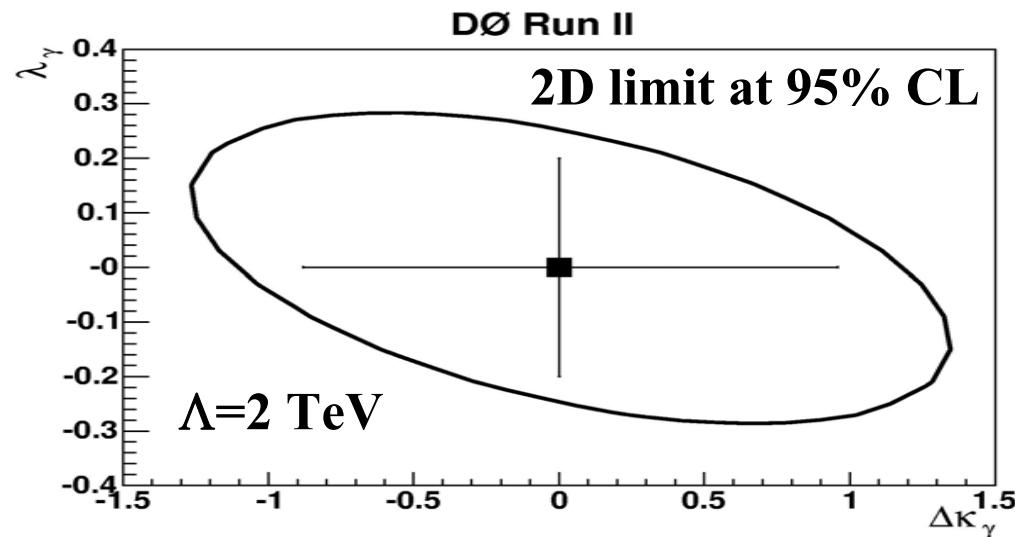
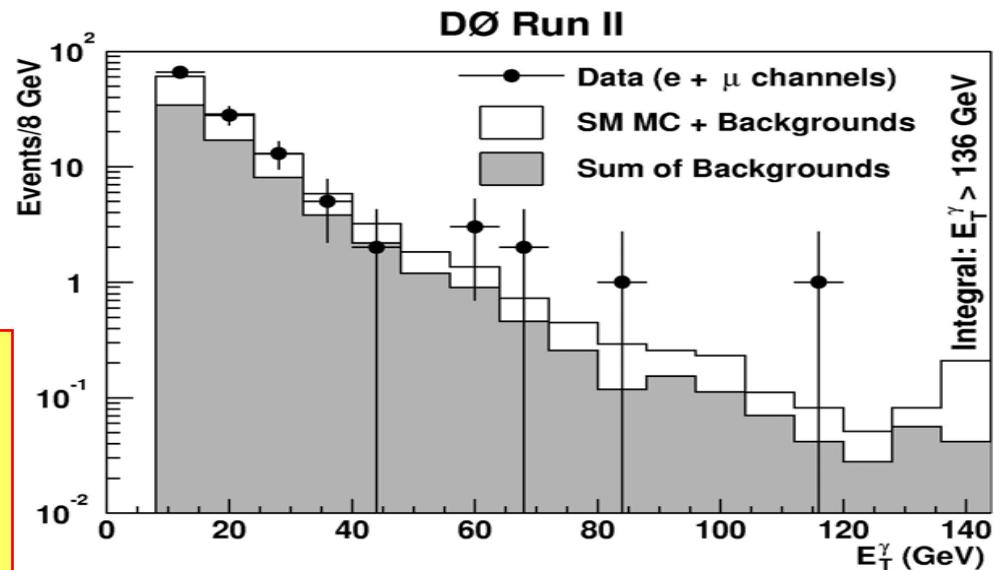
1D limits at 95% C.L.
for $\Lambda = 2 \text{ TeV}$:

$$-0.88 < \Delta\kappa_\gamma < 0.96$$

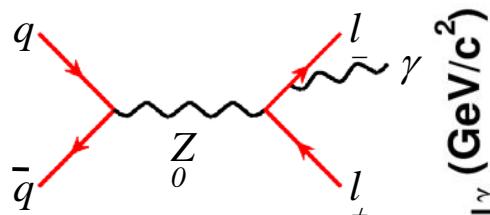
$$-0.20 < \lambda_\gamma < 0.20$$

PRD 71, 091108 (2005)

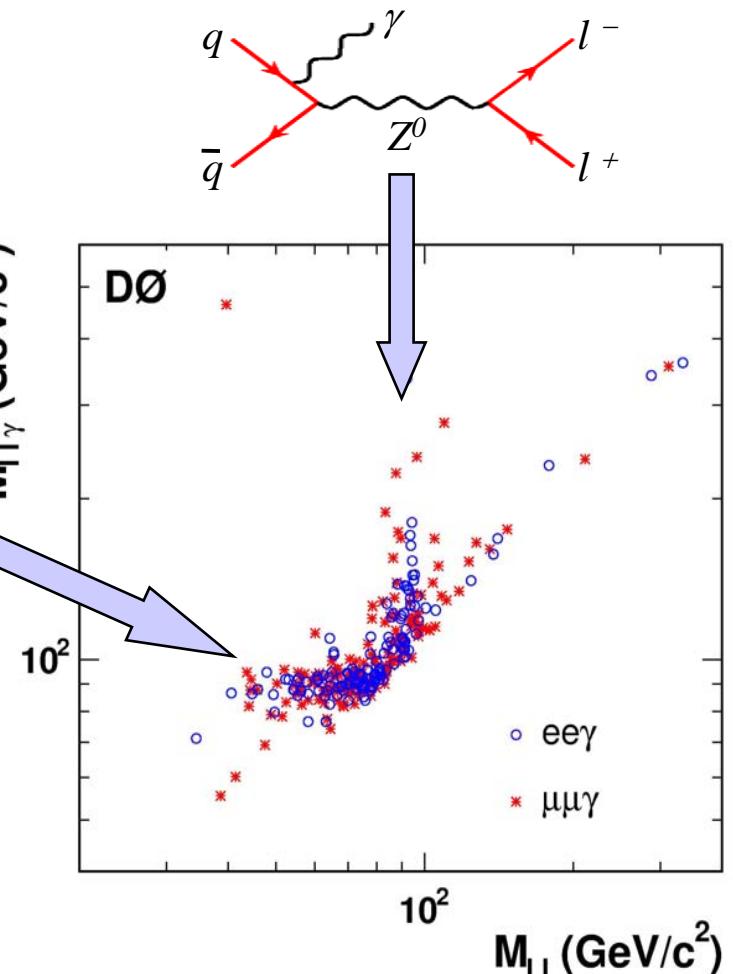
- Important improvement with respect to Run I



- ISR and FSR contribution at tree level,
but no ZZ γ or Z $\gamma\gamma$ vertices in SM



- Study final states with Z decaying to ee or $\mu\mu$
 - events containing ee/ $\mu\mu + \gamma$
- Main background from Z+jet(s) where jet mis-identified as γ .
- Theoretical cross section ~4-5 pb
(U.Baur, T. Han and J. Ohnemus, PRD 57, 2823 (1998))





Z γ Production



Channel	ee γ	DØ	$\mu\mu\gamma$	ee γ	CDF	$\mu\mu\gamma$
$\int L dt, pb^{-1}$	324		286	202		192
SM Z γ	109 ± 7		128 ± 8	31.3 ± 1.6		33.6 ± 1.5
Total Bkgd	23.6 ± 2.3		22.4 ± 3.0	2.8 ± 0.9		2.1 ± 0.7
# Observed	138		152	36		35
A* ε	11.3%		11.7%	3.4%		3.7%
$\sigma^* BR, pb$	-		-	$4.8 \pm 0.8 \pm 0.3$		$4.4 \pm 0.8 \pm 0.2$

● Cross section from combined electron and muon channels

DØ: $\sigma((Z \rightarrow \ell\ell)\gamma, E_T^\gamma > 8 GeV, \Delta R(\ell, \gamma) > 0.7) = 4.2 \pm 0.4(stat + sys) + 0.3(lumi) pb$

SM expectation : $3.9 \pm 0.2 pb$

PRL 95, 051802 (2005)

CDF: $\sigma((Z \rightarrow \ell\ell)\gamma, E_T^\gamma > 7 GeV, \Delta R(\ell, \gamma) > 0.7) = 4.6 \pm 0.6 pb$

SM expectation : $4.5 \pm 0.3 pb$

PRL 94, 041803 (2005)

- Effective Lagrangian has 8 coupling parameters:

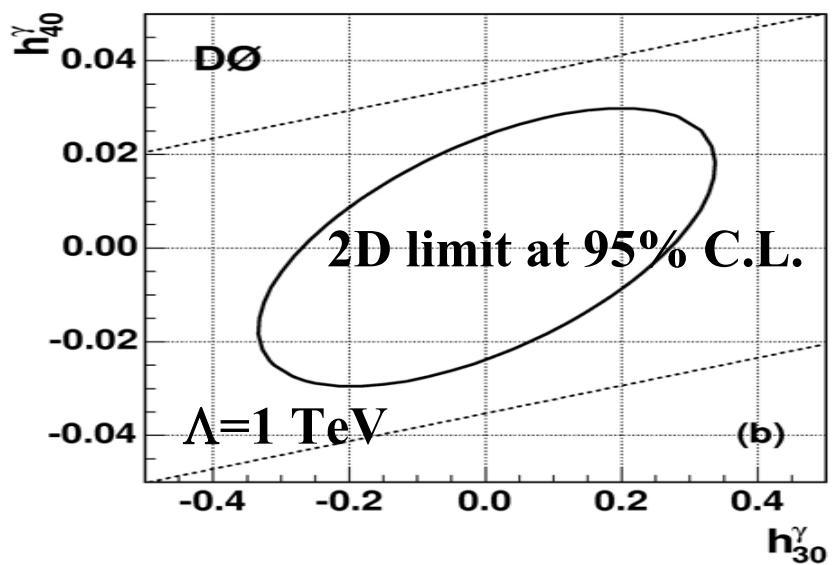
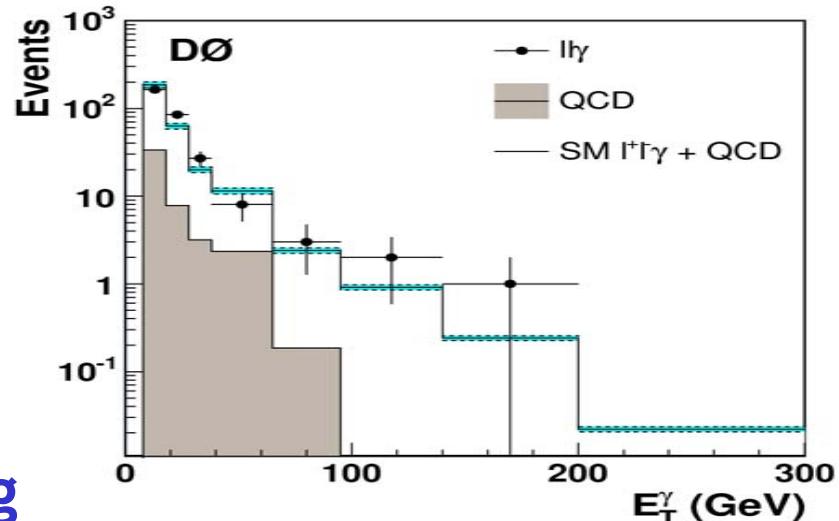
- $h^V_{10}, h^V_{20}, h^V_{30}, h^V_{40}$ ($V=Z, \gamma$)
- All of these = 0 in SM

- Photon E_T sensitive to presence of anomalous coupling

1D limits at 95% C.L. for $\Lambda=1$ TeV
 $|h^{\gamma}_{10,30}| < 0.23, |h^{\gamma}_{20,40}| < 0.019$
 $|h^Z_{10,30}| < 0.23, |h^Z_{20,40}| < 0.020$

PRL 95, 051802 (2005)

- Most stringent limits to date





Summary



- **Most of Run I measurements re-established; many improved and new Run II results:**

- Significant number of diboson candidate events
- Good agreement with the SM
- measured $\sigma(WW)$ using the dilepton decay channel
- first evidence of WZ production
- Model independent limits on WWZ anomalous coupling using WZ events.
- WWZ/WW γ anomalous coupling limits from WW/WZ $\rightarrow l\nu jj$ final states
- Measured W γ and Z γ production cross sections and extracted corresponding anomalous coupling limits

- **More to come:**

- Lots of more data to come/analyze
- Expect to observe Radiation Amplitude Zero in W γ production
- Measure Quartic couplings

